Wedge Filters for Spectral Imaging in the Near IR Using Metal Grids

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Abstract

Linear Variable Filters (LVF's or "wedge filters") have found increasing applicability in spectrally selective optical instruments. They serve as moderate resolution spectral discriminators in astronomical instruments and in reconnaissance equipment. They perform extremely well as "sliding out-of-band blocking filters" when used in conjunction with grating spectrometers.

Visible band LVF's fabricated using traditional interference filter technology have become available and form the basis of a number of spectral imager and imaging spectrometer designs. The desire to extend the instrumentation into the infrared region has been often stated. Additionally, commercial providers of devices using LVF's desire readily available parts and consistent specification.

We have manufactured wedge filters covering the 2.5 - 5 μm spectral range by patterning thin metal films using the electron beam lithography technique. Arrays of apertures with varying size and pitch were manufactured in a gold layer deposited on a calcium fluoride substrate. This technique produces large area arrays (1 cm × 1 cm), offers high reproducibility and allows arbitrary tailoring of the bandpass wavelength versus position profile, unlike dielectric layer interference wedge filters that offer linear grading only. The opportunity to specify a particular wavelength versus position sequence to emphasize certain spectral regions is very attractive to both commercial and government agency users.

In manufacturing these filters we have relied on exact electromagnetic analysis that accounts for the grid periodicity, element shape, and material parameters. This analysis allows design of the center wavelength and bandwidth for the given application with the predicted results matching well with the measured response.

We will discuss the application to astronomical instrumentation, theory of operation, the manufacturing technique, and its current limitations and possible means of improvement.

The most recent theoretical and experimental results will be presented.

Introduction

Use of narrow-band transmission filters to provide spectral discrimination in imaging systems has been practiced for over a hundred years. As airborne and satellite imagers came into being, the need to accomplish this function in a remote sensing instrument was recognized. The concept of using many narrow-band filters to separate spectrally distinctive features was first used, leading to the idea that continuous spectral coverage could be obtained if a filter could be devised where the transmission wavelength varied with the location of the image on the filter. An implementation of this idea using multi-layer dielectric coatings has been developed by many optical filter manufacturers. These filters came to be know as linear variable filters (LVF's). An instrument using this technology for spectral selection was implemented by Pellicori and Mica at SBRC leading to a patent for a Wedge Imaging Spectrometer[1]. Another use for these filters is found on the Thermal InfraRed Imaging Spectrometer (TIRIS) where a diffraction grating is used as the primary spectral discriminator and the LVF as a "sliding out-of-band blocking filter" to prevent radiation from grating high-order terms or from instrumental sources from reaching the detector[2].

Linear variable filters made to date have been, with few exceptions, 'linear'. That is, the variation of transmission has been directly proportional to location on the filter. Additionally, the bandwidth has been a constant percentage of the local center wavelength, precluding constant bandwidth spectrometry when used as the primary discrimination element. This characteristic is also undesirable in a filter used as an out-of-band blocker since the bandwidth of grating dispersed radiation is nearly constant over the spectral ranges commonly used in imaging spectrometers.

The manufacture of interference coatings has not lent itself to variation within the process. Once begun, the deposition of coatings proceeds in a more or less linear fashion. It has been recognized that many applications would benefit from a more selective process, that is, one where the scale factor (wavelength *vs.* location) could be tailored to emphasize certain spectral 'windows' and ignore or minimize others. The development of a means to accomplish this promises much greater flexibility in the availability of "LVF's".

The filters described in this paper are derived from patterned arrays that are mathematically described; thus, they can be computer generated and scaled as required to match specific detector sizes. The arrays can be made "non-linear" and highly selective as required by specific applications.

Design of Variable Filter Arrays

The variable filter array consists of an array element within a two-dimensional periodic cell. The filter bandwidth, center frequency and polarization properties are dependent upon the shape and size of this element. Different element shapes are used for different applications depending on the design specification.

For the infrared spectral imaging application, a narrow bandwidth response given random polarized fields is desired. This specification leads to a crossed-slot element, perhaps sandwiched in a multi-layer structure consisting of two or more layers of crossed-slots. The sandwich structure is used to reduce the bandwidth from that of a single layer.

The design of this structure is completed by computer simulation. A mathematical model of a large array -- 10's of elements in each direction -- is used. Modeling the 'infinite' array reduces the analysis to that of a single element, making it numerically tractable. Since element sizes are on the order of a wavelength, an electromagnetic boundary value problem is constructed and solved numerically. This analysis includes the element shape, polarization of the fields, material parameters, and any possible sandwich structure of layers. To allow for a rather general element shape, the geometry is modeled using a set of piecewise basis functions as in a CAD model. These piecewise functions allow shapes that better model the structures built using electron beam lithography and the electron-resist processing. The result of the computer simulation and design is the geometry of a filter with desired bandwidth and center frequency.

The analysis of a filter array begins by writing a Floquet representation for the fields scattered from the induced periodic current on the structure[3]. In this formulation the currents on the metal structure are modeled, including an approximation for the ohmic losses of gold in the near infrared. Boundary conditions are applied at the surface of the gold metal regions resulting in an integral equation for the unknown induced currents. Since the structure is periodic in two dimensions, the resultant equation is a discrete sum nearly identical to a discrete Fourier transform. The resultant discrete Fourier transform is exploited by modeling the induced current with equally spaced basis functions, resulting in an equation for the currents that is computed using the fast Fourier transform. This formulation produces a numerically efficient method for computing the induced currents on the periodic structure.

From the solution for the induced currents, the reflection and transmission coefficients for the spectral harmonics are calculated. Since an array which allows only the dominant harmonic to propagate is designed, only the (0,0) reflected and transmitted harmonic is calculated, all others being evanescent. These coefficients are optimized for the design specifications and are shown in comparison to the measured results in this paper.

To reduce the bandwidth of the passband, it is possible to cascade multiple arrays spaced appropriately. The cascade structure allows more degrees of freedom in the design so as to tailor the response of the filter. In the infrared spectral imaging application we wish to narrow the passband, therefore two identical filters are placed in a sandwich structure. The analysis of a sandwich structure can be accomplished through a cascade connection of the scattering parameters of the individual filter arrays. A complete set of generalized scattering parameters up to some order (to produce a numerically convergent result) is produced for the first array and then combined with the second structure after propagating the harmonics through the intermediate medium[4]. In our design the intermediate medium will be air since the arrays are held together by a photoresist frame. From the cascade connection of scattering parameters, the overall transmission and reflection coefficients of the sandwich filter are calculated.

The theoretical operation of a filter array, as well as its mathematical and numerical analysis, depends upon the incident field having linear amplitude and phase across the array surface. This linear field distribution produces a resonance in the fields across the array periodic cells, and the near total transmission of the field at the resonant wavelength. The filter response as a function of wavelength is a result of being off this resonant wavelength. When the incident field deviates from the linear field distribution at the array surface, the resonant response will differ from theoretical operation. When used in conjunction with high F number lenses, and when placed at the beam waist of the lens field, the filter response will closer resemble ideal operation. If the incident field phase front is highly curved (when not at the beam waist or when a very low F number lens is used) degradation in the ideal filtering response results.

Manufacturing

Near infrared mesh filters have been successfully manufactured by electron-beam lithography by Byrne *et al*[5]. This group manufactured patterns using direct-write electron beam (e-beam) lithography on PMMA. More recently, focused ion beam (FIB) lithography process have been developed for producing frequency selective metal mesh patterns[6,7].

While both direct write on PMMA and FIB techniques enable patterns with fine line features (better than 200 nm), they are not suitable for wedge filter manufacture. The FIB technique involves stepping of a mask and therefore can not produce patterns of elements with varying pitch without stitching discontinuities. The use of PMMA would lead to prohibitively long writing times for the pattern sizes required to cover a typical wedge filter area. Since our writing time can not exceed 64 hrs., the filter area would be limited to 6-7 mm^2. We have adopted a processing sequence similar to the one described by Atkinson et al[8]. We utilized Shipley 601 negative e-beam resist which reduces the required exposure and, consequently, the writing time approximately 40-fold. This allows us to write arrays as large as 250 mm^2.

In brief, the processing sequence is as follows. First, a layer of PMMA was spun on the CaF_2 substrate. The layer was cured at 170°C and then covered with 100 A of Ge via thermal evaporation. The e-beam resist (Shipley-601) was spun over the Ge layer, cured and exposed. The developed resist served as a mask for patterning the Ge layer by the reactive ion etching (RIE) using CF_4. Then the PMMA was patterned in low pressure oxygen RIE using the Ge layer as a mask. These processing steps transferred the written pattern onto the PMMA layer that was used for a metal lift-off. The metal was 800 A gold layer with 60 A Cr strike layer. The electron micrograph of a sample before metal deposition is shown in Fig. 1. A micrograph of a completed mesh filter is shown in Fig. 2.

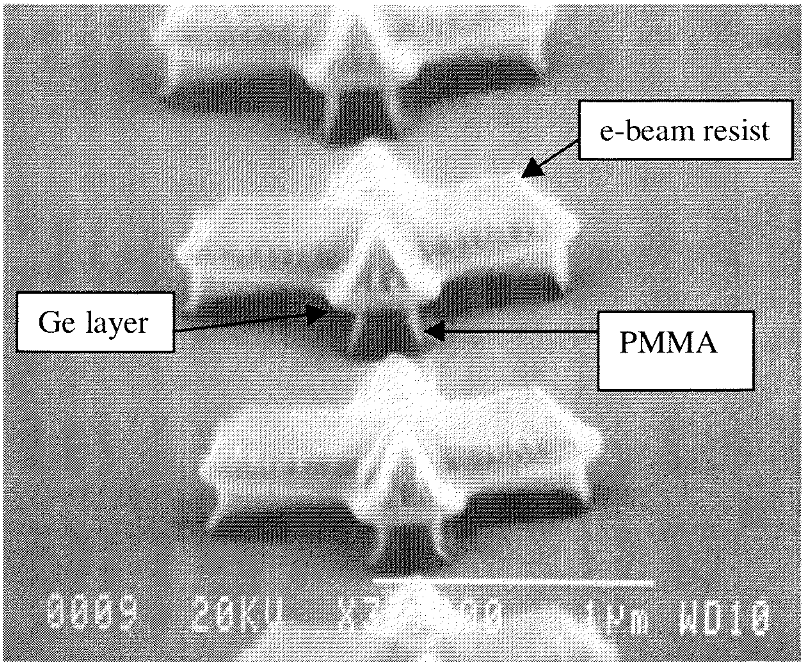

Figure 1. Micrograph of intermediate process step

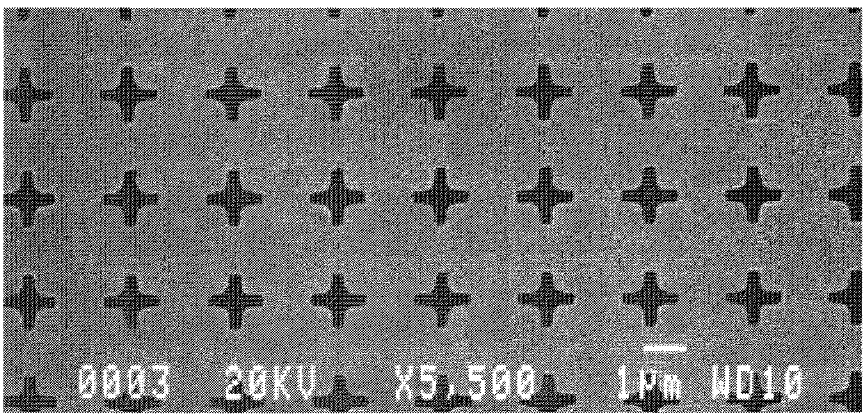

Figure 2. Mesh filter micrograph

Test Results

We have produced and measured a wide area (1 cm^2) single wavelength filter. In Figure 3 we present the comparison of the calculated and measured transmittance curves. The measurements were performed using a Beckman IR4250 Spectrophotometer in an f/10 beam. The calculated and measured curves agree well. The filter has very good rejection at wavelengths longer than the center of the pass band. There is an undesirable transmission band on the shorter wavelength side that turned out to be somewhat larger than predicted. The main transmittance peak parameters are summarized in Table 1.

Table 1. Single filter bandpass characteristics.

	T_{max}	λ_{max} (μm)	$\Delta\lambda$ (μm) FWHM
Calculated	0.95	4.00	0.40
Measured	0.88	3.97	0.28

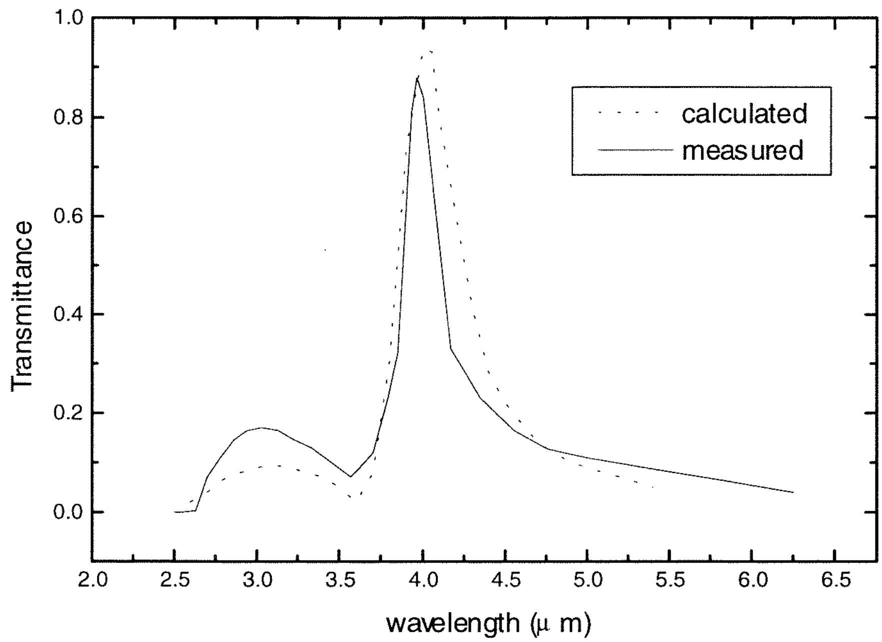

Figure 3. Calculated and measured single filter transmittance.

In order to explore the possibility of narrowing the pass band and reducing the undesirable short wavelength leakage, we have constructed a double filter made of two identical mesh filters placed in close proximity to each other. One of the two filters in the pair had a 3 μm thick photoresist frame defined around the mesh area; the filters were squeezed together in an aluminum holder. In Figure 4 we present the transmittance curves for a single filter and a double filter. The data have been taken using a Mattson Instruments FTIR spectrometer with the beam divergence cut to f/10. The measured single filter performance is worse than in the f/10 beam of the Beckman spectrophotometer. At this time we can not fully account for this difference. The center wavelength, maximum transmittance, and line width (FWHM) are summarized in Table 2. Notice excellent rejection at long wavelength side. Even for the single filter the transmittance is less that 0.5% from 6 to 25 μm.

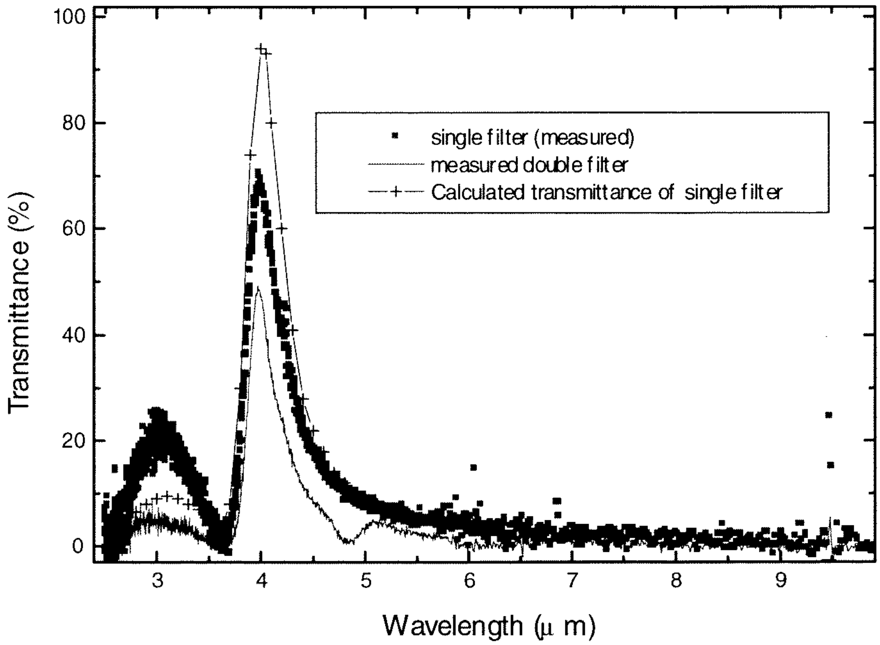

Figure 4. Double vs. single filter transmittance.

Table 2. Measured double *vs.* single filter characteristics

	T_{max}	λ_{max} (μm)	Δλ (μm) FWHM
Single filter (measured)	0.7	3.98	0.41
Single filter (calculated)	0.95	4.00	0.40
Double filter (measured)	0.49	3.98	0.32

The filters described above can be manufactured as spatially wavelength variant by varying the geometry (spacing and scale of the array elements). One such filter has been fabricated and tested in the Beckman IR 4250 Spectrophotometer using the JPL Micro Scale Test Adjunct[9]. To facilitate testing, the filter has been implemented as a series of eleven one-millimeter wide constant wavelength stripes. The transmittance *vs.* position on the filter is shown in Figure 5a for three of the stripes. The predicted and measured spectral positions of the passbands are in good ageement as shown in Figure 5b.

The passbands measured on the variable filter are much wider than predicted ($\delta\lambda/\lambda \approx 0.1$, FWHM). We attribute this to the measurement being made in the f/1 beam produced by the JPL Micro Scale Test Adjunct. Such rapidly convergent beam could result in highly curved wavefront leading to degradation of the filtering response as discussed above.

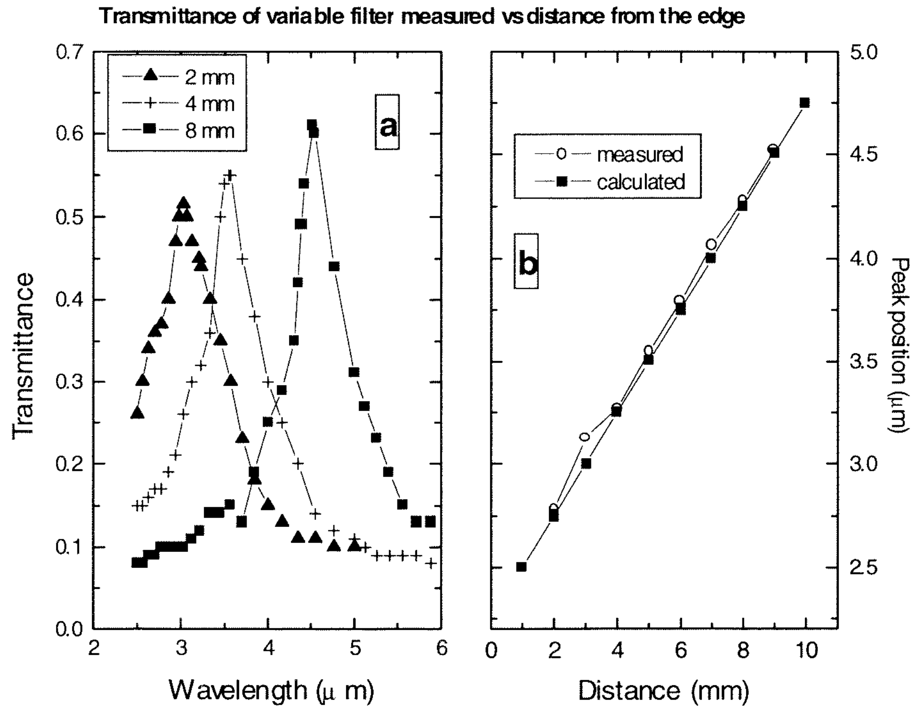

Figure 5. Variable filter transmittance vs. distance from the filter edge.

Conclusions

We have demonstrated wedge filters using metal grids in 2.5-5 µm range. The filters are best used in high f-number beams, otherwise their performance is degraded. While the filters have excellent long wavelength blocking qualities, they have undesirable pass band on the short wavelength side of the main peak. We demonstrated that this can be alleviated by using two stage filters. The technology allows flexibility in designing filters that are graded in non-linear fashion to accentuate the pass bands of interest.

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References

1. S. F. Pellicori; A. M. Mica; U. S. Patent 4,957,371, **Wedge Filter Spectrometer**, September 18, 1990.

2. La Baw, C. **Thermal Infrared Imaging Spectrometry with Room Temperature Optics**, Proc. Intl. Symposium on Spectral Sensing Research, 1993 *and* Proc. SPIE

OE/LASE '93, Vol. 1874, No. 29, 1993

3. Cwik T. and Mittra R., **Scattering from a periodic array of free-standing arbitrarily shaped perfectly conducting or resistive patches,** IEEE Trans. Antennas Propag., vol. AP-35, no. 11, pp. 1226-1233, Nov. 1987.

4. Cwik T. and Mittra R, **The cascade connection of planar periodic surfaces and lossy dielectric layers to form an arbitrary periodic screen**, IEEE Trans. Antennas Propag., vol. AP-35, no. 12, pp. 1397–1405, Dec. 1987.

5. D. M. Byrne, A.J. Brouns, F.C. Case, R.C. Tiberio, B.L. Whitehead, and E.D. Wolf. **Infrared mesh filters fabricated by electron-beam lithography**. J. Vac. Sci. Technol. B 3 (1) pp. 268-271 (1985).

6. J.C. Wolfe, S.V. Pendharkar, P. Ruchhoeft, S. Sen, M.D. Morgan, W.E. Horne, R.C. Tiberio, and J.N. Randall. **A proximity ion beam lithography process for high density nanostructures.** J. Vac. Sci. Technol. B 14 (6) 3896-3899 (1996).

7. M.D. Morgan, W.E. Horne, V. Sundaram, J.C. Wolfe, S.V. Pendhakar, R. Tiberio. **Application of optical filters fabricated by masked ion beam lithography**. J. Vac. Sci. Technol. B 14 (6) 3903-3906 (1996).

8 G.M. Atkinson, R.L. Kubena, L.E. Larson, L.D. Ngyen, F.P. Stratton, L.M. Jelloian, M.V. Le, and H. McNulty. **Self-aligned high electron mobility transistor gate fabrication using focused ion beams.** J. Vac. Sci. Technol. B 9 (6) 3506-3510 (1991)

9. La Baw, C. **Measuring Spatially Varying Transmittance of a Filter**, NASA Tech Briefs, pg. 66, September 1992